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Ranking South African provinces on the basis of MERRA 2D surface incident shortwave flux

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Abstract

The main objective of the present study is to rank South African provinces on the basis of incoming solar radiation. The surface incident shortwave flux (SW_{Flux} , Wm^{-2}) of NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA 2D) reanalysis data for the period 1980–2009 over South Africa was analysed on annual, seasonal and monthly scales. The monthly mean \pm standard deviation values of SW_{Flux} for the period revealed that, Northern Cape received the most ($267.38 \pm 4.32 Wm^{-2}$) incoming solar radiation throughout the year, followed by North West ($263.37 \pm 7.13 Wm^{-2}$) and Free State ($259.20 \pm 7.66 Wm^{-2}$). The northern region of Limpopo also showed a good amount of incoming solar radiation ($257.95 \pm 6.16 Wm^{-2}$) at the surface. KwaZulu-Natal received least ($232.99 \pm 7.02 Wm^{-2}$) amount of mean monthly solar radiation in comparison with other provinces. On an annual scale, the Northern Cape ranked first, and on seasonal and monthly scales North West ranked first. Limpopo and Free State also performed well in the present study.

Keywords: solar radiation, solar energy, reanalysis data

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1. Introduction

Solar radiation mainly reaches the earth's surface in the form of shortwave radiation. With a changing climate, the amount of solar radiation reaching the earth's surface is also changing. In this regard, the monitoring and analysis of solar radiation over a region is important. Satellite data is good for the analysis of solar radiation because of its better spatial coverage compared to the ground measurements.

The sun is also the source of solar energy. Efficient use of solar energy not only decreases reliance on fossil fuels, but will also reduce environmental degradation associated with fossil fuels (Atilgan and Azapagic, 2015; Singh et al., 2011). Its availability over the earth's surface varies from place to place due to factors including latitude, elevation and cloud cover. The geographic location of South Africa is highly favorable for solar energy-based applications. Previous studies (Schulze and McGee, 1976; Drummond and Vowinkel, 1957) indicate that over South Africa daily insolation may reach up to 29 MJm^{-2} . The population of South Africa is over 50 million and to satisfy energy demand sustainably renewable energy is necessary. Development of any country's renewable energy potential is important for sustainable development. Solar energy is considered as the most reliable renewable energy resources (Kleissl, 2013). It is freely available, but collecting and transforming it is not very much cost-effective (Kougias et al., 2016). Means of collecting solar energy include photovoltaic systems (PV), solar thermals (solar water heaters, solar hot water panel, solar hot water collector), and solar thermal and PV working together. Before installing any solar energy collecting device at any site it is advisable to perform a detailed analysis of the site, as any wrong information may lead to sub-optimal performance and unexpectedly poor economic returns. For example, the size and design of PV systems to be installed at any site should be decided after proper solar resource assessment (Munzhebdi and Sebitosi, 2009). To assess a site's solar energy potential, long-term solar radiation data is needed. Typical meteorological year (TMY) data have been also used in many solar resource assessment studies (Kleissl, 2013) - that is, a long-term average of solar irradiance. TMY data, which represent the typical conditions, might be less useful where substantial variability and extremes in weather are observed.

While information related to incoming solar radiation is valuable, observational solar radiation data is sparse. Radiometric stations provide data for single locations and sometime for a relatively short duration. In this case, satellite data are reliably sourced. There is no doubt that *in situ* observations are valuable but satellite data are arguably a better option due to their better spatial coverage. It is nec-

essary to understand the characteristics of data carefully in order to use them for solar resource assessment, as requirements for different projects vary. The focus of solar radiation project on a PV installation requires mainly global horizontal irradiance (GHI) dataset, while concentrating solar power needs a direct normal irradiance (DNI) dataset. For some solar projects, exceedance probabilities (P10, P50, P90, P95 and P99) of GHI and DNI are also calculated. The present study aims to study SW_{Flux} , from MERRA 2D reanalysis data (1980–2009) over the nine provinces (see details in Section 2). SW_{Flux} data were analysed in all the provinces separately to understand its variation on provincial scale. The provinces were also ranked on the basis of available SW_{Flux} . Studies based on rank are useful to convert large information into digestible information and it is easier to remember and present rank than actual values. In many renewable energy studies ranking method has been used (Şengül et al, 2015; Mohamadabadi et al. 2009; Goumas and Lygerou, 2000). Solar energy studies that focus on provinces can help governmental decision-making on a provincial scale. This study can also assist small-to-large solar energy investors, construction engineers, tourism industries and architects to plan activities and make decisions in their respective areas. It can also serve as a baseline for further studies related to solar energy potential using MERRA 2D data.

2. Study area and datasets

South Africa lies between 22° – 34° S latitude and 16° – 32° E longitude. On the west it is bounded by the Atlantic Ocean; on the south and east by the Indian Ocean; on the North by Namibia, Botswana and Zimbabwe; and by Mozambique and Swaziland on the north-east. There are nine provinces: Free State, Northern Cape, Western Cape, Gauteng, Mpumalanga, North West, Limpopo, KwaZulu-Natal and Eastern Cape (Figure 1). There are four primary climatic zones: desert (Northern Cape, North-Eastern parts of Western Cape); arid (Lim-



Figure 1: The provinces of South Africa.

popo, Mpumalanga, North-West, Free State, the western parts of KwaZulu-Natal and the Eastern Cape); sub-tropical wet (coastal strip of KwaZulu-Natal and the Eastern Cape); and Mediterranean winter rainfall (south-western coastal strip of Western Cape) (JWAF, 1999).

Monthly MERRA 2D datasets going back to 1979 were released in 2010 by the NASA, with data generated using Version 5 of the Goddard earth observing system atmospheric model and data assimilation system (Rienecker et al., 2011). These datasets are widely used in the scientific community (Chand et al., 2016; Bosilovich et al., 2011; Robertson et al., 2011; Schubert et al., 2011). The spatial resolution of the datasets is $2/3^\circ$ (longitude) \times $1/2^\circ$ (latitude). More details on MERRA 2D data can be found at <http://giovanni.sci.gsfc.nasa.gov/giovanni/>. The present analysis used MERRA 2D monthly SW_{Flux} .

3. Methodology

SW_{Flux} data (1980–2009) were used to calculate long-term annual, seasonal and monthly means along with standard deviation (SD). These data were separated into three decades 1980s (1980–1989), 1990s (1990–1999) and 2000s (2000–2009) and analysed for annual, monthly and seasonal averages. Three metrics were calculated in order to compare the solar energy potential (based on the mean values) of provinces: solar energy potential number (SEPN), total solar energy potential number (TSEPN), and solar energy potential rank (SEPR). SEPN was calculated first by determining the mean values of SW_{Flux} for each province, and those with maximum (minimum) SW_{Flux} were given a SEPN value of 1 (9), respectively. The same procedure was applied for annual, seasonal and monthly time scales. TSEPN was calculated as the sum of all the SEPNs. The smallest TSEPN was given the first rank and the largest TSEPN was given the last rank. The provinces where the values of SW_{Flux} were equal were given equal rank.

4. 4. Results and discussions

4.1 Spatial variation of SW_{Flux} from 1980 to 2009

Solar radiation at any location depends upon the land elevation, sunshine duration, cloud cover, moisture and dust content (Singh et al., 2013; Drummond and Vowinkel, 1957). Figure 2 shows spatial variation of the annual mean SW_{Flux} in South Africa from 1980 to 2009, where it can be clearly observed that the north and north-west regions of South Africa receives more solar radiation than the south and south-east. Annual, monthly and seasonal means are presented as mean \pm SD. The monthly mean values of SW_{Flux} (1980–2009) show that Northern Cape received the highest ($267.38 \pm 4.32 \text{ Wm}^{-2}$) incoming solar radiation

throughout the year, followed by the North West ($263.37 \pm 7.13 \text{ Wm}^{-2}$) and Free State ($259.20 \pm 7.66 \text{ Wm}^{-2}$); Limpopo also received a good amount of SW_{Flux} ($257.95 \pm 6.16 \text{ Wm}^{-2}$), while KwaZulu-Natal received the least ($232.99 \pm 7.02 \text{ Wm}^{-2}$). The mean magnitude of percentage difference with respect to Northern Cape was also calculated (Table 1). The maximum was recorded by KwaZulu-Natal at 12.86% and the minimum by North West at 1.50%.

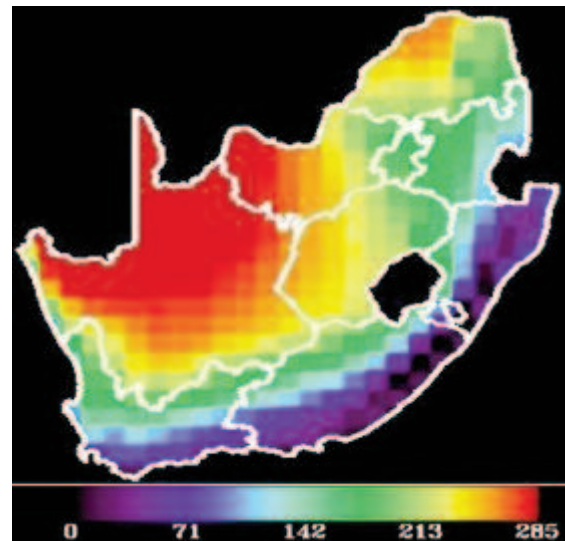


Figure 2: Variation of annual mean of SW_{Flux} (surface incident shortwave flux, Wm^{-2}) from 1980 to 2009.

Table 1: Mean with standard deviation (mean \pm SD) of SW_{Flux} in nine provinces and magnitude of percentage difference with respect to Northern Cape.

Province	1980–2009 (Mean \pm SD)	% difference from N. Cape
Free State	259.20 ± 07.66	3.06
Northern Cape	267.38 ± 04.32	0.00
Western Cape	244.34 ± 03.10	8.62
Gauteng	252.78 ± 07.46	5.46
Mpumalanga	247.49 ± 06.46	7.44
North West	263.37 ± 07.13	1.50
Limpopo	257.95 ± 06.16	3.53
KwaZulu-Natal	232.99 ± 07.02	12.86
Eastern Cape	236.06 ± 05.98	11.71

4.2 Variation of SW_{Flux} in different seasons

Figures 3 and 4 show that, SW_{Flux} varied from season to season for the nine provinces. Northern

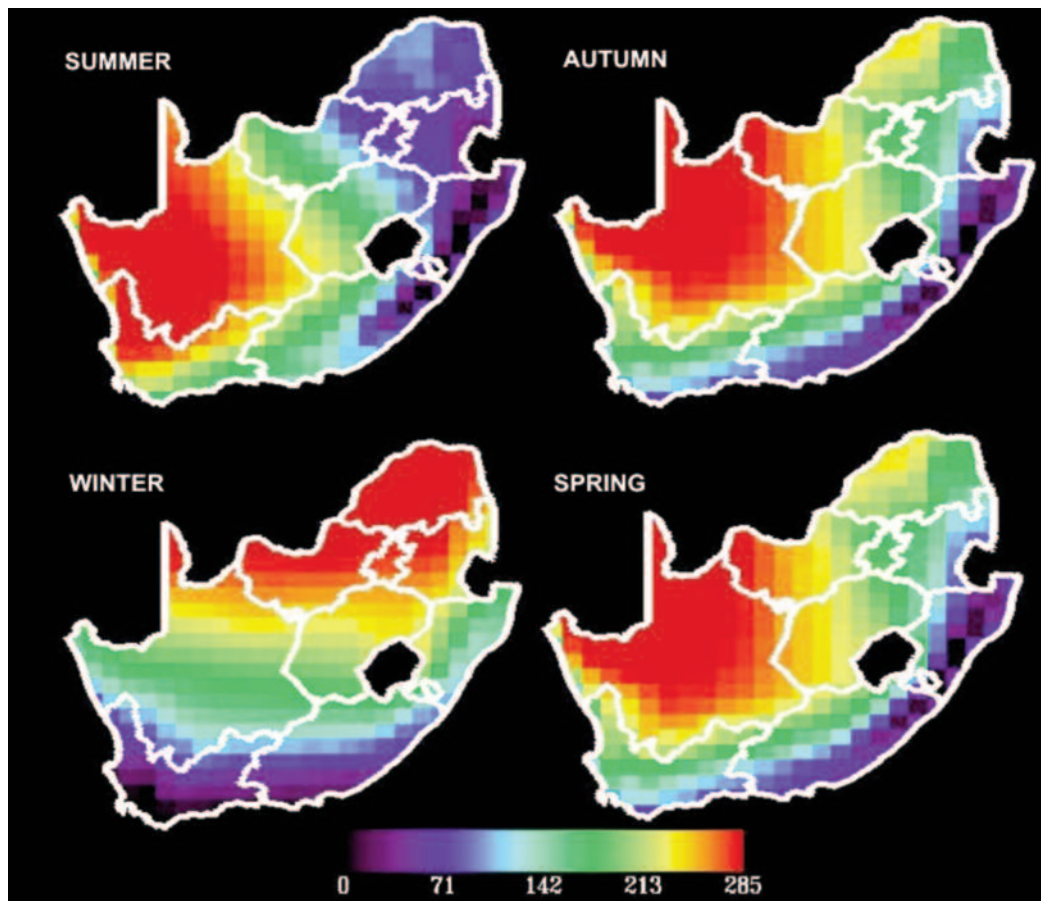


Figure 3: Climatological mean of monthly means of SW_{Flux} (surface shortwave incident flux, W/m^2) from MERRA 2D reanalysis (1980–2009), by season.

Cape showed more SW_{Flux} in summer than any other provinces, while Limpopo had more SW_{Flux} in autumn ($235 \pm 4.61 Wm^{-2}$) and winter ($201.60 \pm 4.7 Wm^{-2}$). During summer, autumn, winter and spring the maximum (minimum) SW_{Flux} was in Northern Cape, $357.57 \pm 7.51 Wm^{-2}$ (KwaZulu-Natal, $288.714 \pm 10.02 Wm^{-2}$), Limpopo, $235 \pm 4.61 Wm^{-2}$ (Eastern Cape, $199.74 \pm 11.36 Wm^{-2}$), Limpopo, $201.60 \pm 4.39 Wm^{-2}$ (Western Cape, $141.31 \pm 8.57 Wm^{-2}$), and Northern Cape, $310.40 \pm 6.9 Wm^{-2}$ (KwaZulu-Natal, $264.41 \pm 10.76 Wm^{-2}$), respectively, as shown in Figure 4. Most areas in the Northern Cape during the winter showed less amount of SW_{Flux} . The monthly mean of SW_{Flux} with SD for 1980–2009 in the nine provinces is presented in Table 2, which shows that during the winter and autumn months Limpopo had higher SW_{Flux} than other provinces. Present studies of SW_{Flux} results on annual and seasonal scale show similarity to the maps generated using the United States National Renewable Energy Laboratory database (Fluri, 2009). These maps show that the solar radiation was higher in Northern Cape during summer and spring and lower in winter. The monthly mean values of SW_{Flux} (1980–2009) with SD are presented in Table 2. In almost all the provinces the SW_{Flux} was higher in December and lower in June.

4.3 Spatial variation of SW_{Flux} over three decades

SW_{Flux} was analysed spatially over the three decades of the datasets – the 1980s, 1990s and 2000s (Figure 5). SW_{Flux} in Northern Cape was higher than in any other province in all three

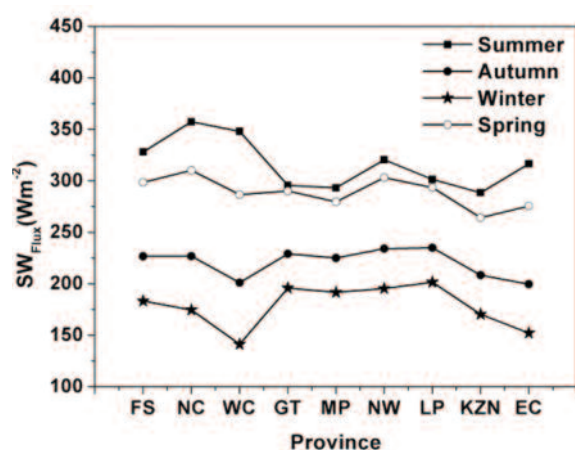


Figure 4: Seasonal variation of surface incident shortwave flux (SW_{Flux}), Wm^{-2} in the nine provinces of South Africa. (FS, NC, WC, GT, MP, NW, LP, KZN and EC stand respectively for Free State, Northern Cape, Western Cape, Gauteng, Mpumalanga, North West, Limpopo, KwaZulu-Natal and Eastern Cape).

Table 2: Monthly mean of surface incident shortwave flux, Wm^{-2} with a standard deviation (SD) for 1980–2009 in the nine provinces of South Africa.

<i>Province</i>	<i>SW_{Flux} (Mean \pm SD)</i>					
	<i>Jan</i>	<i>Feb</i>	<i>Mar</i>	<i>Apr</i>	<i>May</i>	<i>June</i>
Free State	334.45 \pm 16.57	305.80 \pm 8.36	270.28 \pm 3.97	225.09 \pm 3.60	184.94 \pm 5.54	163.31 \pm 6.03
Northern Cape	366.74 \pm 8.41	330.39 \pm 7.31	279.72 \pm 5.12	223.46 \pm 8.61	177.27 \pm 11.56	153.94 \pm 12.59
Western Cape	359.65 \pm 11.46	319.92 \pm 12.70	261.91 \pm 11.65	195.73 \pm 9.81	145.71 \pm 8.77	121.94 \pm 7.84
Gauteng	297.93 \pm 5.37	285.93 \pm 2.90	260.82 \pm 2.99	229.67 \pm 1.06	197.02 \pm 1.28	177.01 \pm 1.82
Mpumalanga	325.53 \pm 3.14	286.72 \pm 3.87	258.23 \pm 3.32	224.53 \pm 4.35	192.55 \pm 4.25	173.56 \pm 4.29
North West	325.53 \pm 16.50	300.26 \pm 9.77	271.14 \pm 5.73	234.22 \pm 2.37	196.98 \pm 3.30	175.69 \pm 3.47
Limpopo	304.72 \pm 2.70	294.37 \pm 4.39	267.59 \pm 4.38	234.93 \pm 4.91	202.48 \pm 4.54	183.21 \pm 3.82
KwaZulu-Natal	291.84 \pm 9.83	277.56 \pm 8.78	246.21 \pm 8.77	207.06 \pm 8.52	172.13 \pm 7.85	152.87 \pm 7.38
Eastern Cape	324.41 \pm 19.17	291.27 \pm 14.21	248.47 \pm 11.67	196.00 \pm 11.11	154.00 \pm 11.30	133.03 \pm 11.02
	<i>July</i>	<i>Aug</i>	<i>Sept</i>	<i>Oct</i>	<i>Nov</i>	<i>Dec</i>
Free State	174.53 \pm 6.16	212.17 \pm 4.76	264.44 \pm 3.74	299.65 \pm 6.32	331.56 \pm 12.86	344.23 \pm 17.85
Northern Cape	164.82 \pm 12.07	205.33 \pm 11.80	261.02 \pm 9.65	314.41 \pm 5.65	355.76 \pm 5.43	375.58 \pm 6.81
Western Cape	131.78 \pm 8.61	170.58 \pm 9.26	229.78 \pm 9.41	291.69 \pm 10.39	338.63 \pm 10.43	365.10 \pm 11.00
Gauteng	187.96 \pm 1.69	223.07 \pm 1.51	270.49 \pm 0.99	294.46 \pm 2.04	305.63 \pm 5.79	303.35 \pm 7.13
Mpumalanga	183.88 \pm 04.68	217.58 \pm 05.28	261.84 \pm 06.38	284.33 \pm 06.24	293.24 \pm 06.74	295.68 \pm 05.96
North West	186.90 \pm 03.50	223.97 \pm 02.80	273.58 \pm 02.06	305.86 \pm 04.94	330.08 \pm 13.18	336.19 \pm 18.52
Limpopo	193.37 \pm 04.33	228.22 \pm 05.04	272.31 \pm 05.95	301.59 \pm 06.48	306.96 \pm 6.84	305.62 \pm 5.29
KwaZulu-Natal	162.67 \pm 08.01	195.61 \pm 09.17	238.45 \pm 11.29	267.42 \pm 09.56	287.35 \pm 11.42	296.75 \pm 11.45
Eastern Cape	143.85 \pm 11.42	179.89 \pm 12.80	231.28 \pm 13.11	279.38 \pm 12.91	316.07 \pm 14.82	334.25 \pm 18.46

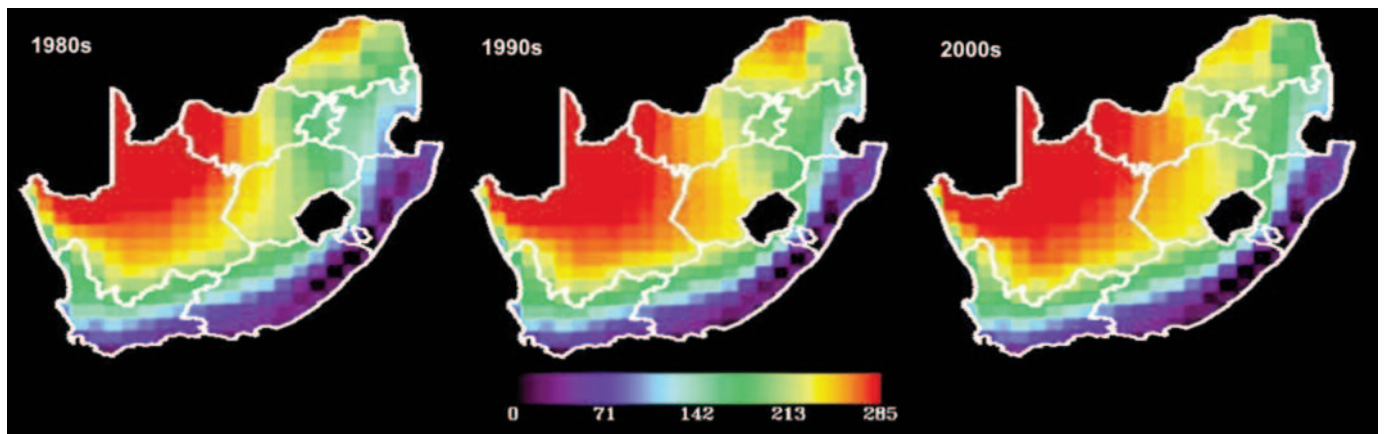


Figure 5: Spatial variation of SW_{Flux} (surface incident shortwave flux, Wm^{-2}) in the last three decades over South Africa.

Table 3: Mean SW_{Flux} (surface incident shortwave flux, Wm^{-2}) with a standard deviation in the last three decades over South Africa.

<i>Province</i>	<i>1980s</i>	<i>1990s</i>	<i>2000s</i>
		<i>(Mean \pm SD)</i>	
Free State	259.27 \pm 11.90	260.00 \pm 4.93	258.34 \pm 4.66
Northern Cape	269.44 \pm 5.60	267.21 \pm 3.26	265.49 \pm 2.33
Western Cape	245.47 \pm 4.73	244.17 \pm 2.04	243.37 \pm 1.40
Gauteng	251.46 \pm 9.88	254.19 \pm 5.94	252.69 \pm 6.51
Mpumalanga	246.46 \pm 8.50	249.48 \pm 4.85	246.53 \pm 5.71
North West	265.56 \pm 9.66	262.62 \pm 5.82	261.92 \pm 5.33
Limpopo	259.98 \pm 5.05	259.61 \pm 6.08	254.24 \pm 6.07
Kwa Zulu-Natal	233.48 \pm 11.12	233.90 \pm 4.07	231.59 \pm 3.98
Eastern Cape	237.12 \pm 9.22	237.29 \pm 2.98	233.76 \pm 3.57

decades, the 1980s (269.44 \pm 5.60 Wm^{-2}), the 1990s (267.21 \pm 3.26 Wm^{-2}) and the 2000s (265.49 \pm 2.33 Wm^{-2}) (Table 3). The spatial variation of SW_{Flux} show that the amount of solar radiation decreased each decade, a trend shared by other five provinces (North West, Limpopo, KwaZulu-Natal and Eastern Cape) (Figure 5). This could be attributed to increasing air pollution, which reduces the amount of solar radiation reaching the earth's surface (Gan et al., 2014, Singh et al., 2012).

4.4 SEPR for the nine provinces of South Africa

SEPR was calculated on annual, seasonal and monthly scales. Annually, the Northern Cape ranked first, followed by North West (Table 4). Seasonally the North West ranked first, followed by Northern Cape and Limpopo. The monthly scale showed that North West again ranked first, followed by Limpopo. KwaZulu-Natal did not performed well on annual, seasonal and monthly. The good solar energy potential of Northern Cape was reported previously (Fluri, 2009). The present study found that North West and Limpopo also showed good solar energy potential (Table 4). Concentrating solar power and PV are important for harvesting solar radiation from the recognised high solar energy potential areas.

5. Conclusions

In order to contribute to better understanding the solar energy potential of different provinces of South Africa, annual, seasonal, and monthly variability in SW_{Flux} was studied using MERRA 2D data (1980–2009). On an annual scale, SW_{Flux} was found to be the highest for Northern Cape (267.4 \pm 4.32 Wm^{-2}), followed by North West (263.3 \pm 7.13 Wm^{-2}) and Free State (259.2 \pm 7.66 Wm^{-2}).

Seasonal scale SW_{Flux} was highest in Northern Cape only during summer (357.57 \pm 7.51 Wm^{-2}) and spring (310.40 \pm 6.9 Wm^{-2}). Limpopo had the highest value of SW_{Flux} in winter and spring; and some of its areas also received a good amount of solar radiation that could serve as good sites for solar energy based applications. SEPR analysis showed that the Northern Cape ranked first on an annual basis, while North West ranked first in seasonal and monthly analyses. The amount of SW_{Flux} over Northern Cape was high. However, North West, Limpopo and Free State also received good amount of solar radiation.

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Table 4: Solar energy potential number (SEPN), total solar energy potential number (TSEPN), and solar energy potential rank (SEPR) on annual, seasonal and monthly scales in the nine provinces of South Africa.

	Free State	N. Cape	W. Cape	Gauteng	Mpumalanga	North West	Limpopo	KwaZulu-Natal	E. Cape
SEPN _{Annual}	3	1	7	5	6	2	4	9	8
TSEPN _{Annual}	3	1	7	5	6	2	4	9	8
SEPR _{Annual}	3	1	7	5	6	2	4	9	8
SEPN _{Summer}	3	1	2	7	8	4	6	9	5
SEPN _{Autumn}	5	4	8	3	6	2	1	7	9
SEPN _{Winter}	5	6	9	2	4	3	1	7	8
SEPN _{Spring}	3	1	6	5	7	2	4	9	8
TSEPN _{Seasonal}	16	12	25	17	25	11	12	32	30
SEPR _{Seasonal}	3	2	5	4	5	1	2	7	6
SEPN _{Jan}	3	1	2	7	8	4	6	9	5
SEPN _{Feb}	3	1	2	8	7	4	5	9	6
SEPN _{Mar}	3	1	5	6	7	2	4	9	8
SEPN _{April}	4	6	9	3	5	2	1	7	8
SEPN _{May}	5	6	9	2	4	3	1	7	8
SEPN _{June}	5	6	9	2	4	3	1	7	8
SEPN _{July}	5	6	9	2	4	3	1	7	8
SEPN _{Aug}	5	6	9	3	4	2	1	7	8
SEPN _{Spet}	4	6	9	3	5	1	2	7	8
SEPN _{Oct}	4	1	6	5	7	2	3	9	8
SEPN _{Nov}	3	1	2	7	8	4	6	9	5
SEPN _{Dec}	3	1	2	7	9	4	6	8	5
TSEPN _{Monthly}	47	42	73	55	72	34	37	95	85
SEPR _{Monthly}	4	3	7	5	6	1	2	9	8

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